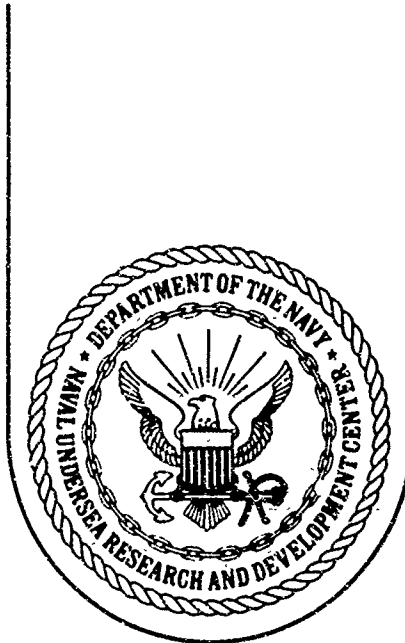


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# FLUID FRICTION OF THE SLIME OF AQUATIC ANIMALS

by

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Fleet Engineering Department

November 1970

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### FOREWORD

There is currently widespread interest throughout the scientific community in studying high polymers that reduce hydrodynamic frictional drag. Many synthetic polymers are known to be effective in reducing friction, and certain biological exudates from algae and bacteria have been identified in hydrodynamic test facilities as friction reducers.

This report considers the friction-reducing properties of the slime of fish and other aquatic animals and hypothesizes a relationship between these properties and a fish's swimming ability. The work was performed during Fiscal Years 1967 and 1968 under Office of Naval Research Project Orders 7-0071 and 8-0014, respectively. Mr. D. E. Holt was the Office of Naval Research program manager. The report was reviewed for technical adequacy by Dr. J. W. Hoyt of this Center.

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## **SUMMARY**

### **OBJECTIVE**

➤ An investigation was undertaken to determine the friction-reducing properties of fish slime. The slime was tested from species of both fresh-water and marine fish and, for purposes of comparison, from the nut-brown cowry.

### **RESULTS**

➤ Most of the species tested displayed a remarkable ability for reducing the friction of turbulent, flowing water. The diluted solution of the slime of one species was measured as nearly 66% lower than the friction of water.

The properties of fish slime were found to be approximately the same for individual fish within the same species. Variations in slime properties within the same species are believed to be dependent on the age and size of the individual fish.

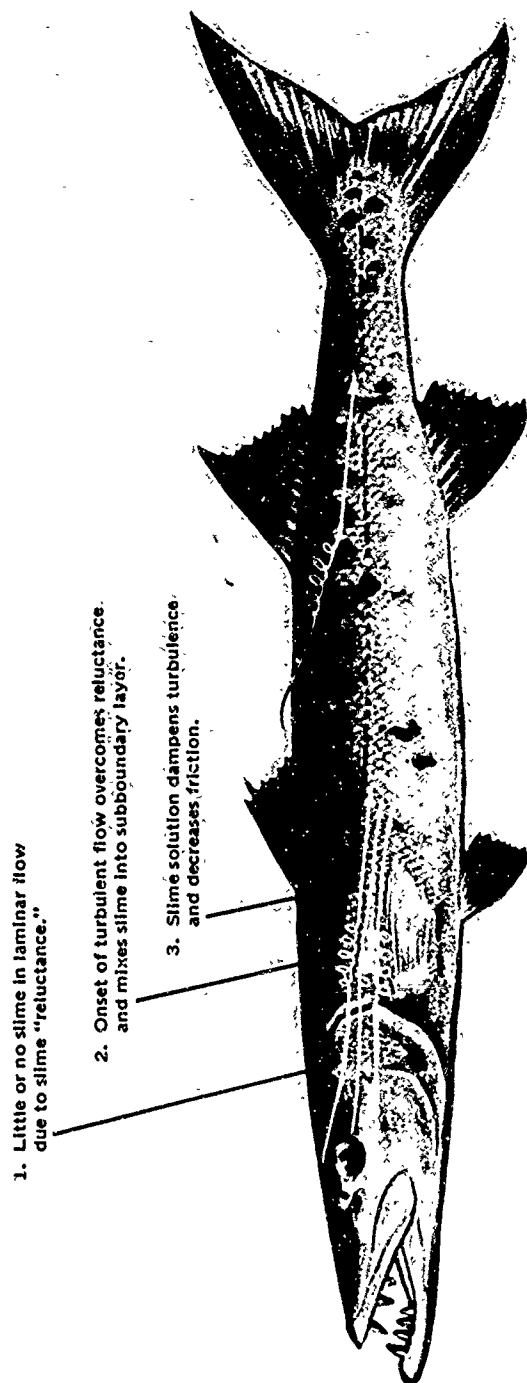
### **CONCLUSIONS**

➤ It is hypothesized that slime properties are dependent on the life habits of the fish and that slime aids a fish's swimming ability.

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Rosen-Cornford hypothesis of action of fish slime.

## INTRODUCTION

Fish are slippery, as is evident to all who have handled them. The fisherman, the fishmonger, the housewife, all know that most fish are covered with a smelly, slimy, slithery substance that makes them difficult to hold.

The external mucus or slime of fish is generated by hundreds of small glands underlying the epithelium and embedded in the epidermis between the scales (Fig. 1). The slime is exuded through minute canals to cover practically every part of the fish's body, including the spiny fins, the soft rayed fins, and the caudal fin (tail).

Slime serves the living animal in many ways:

1. One necessary function of slime is to supply lubrication between the scales as the body flexes.

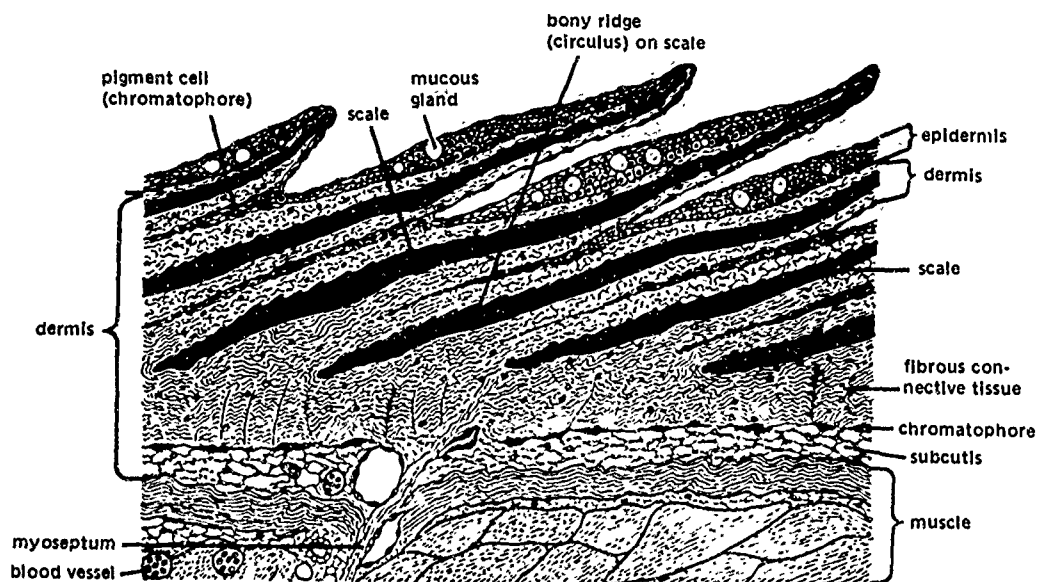


Figure 1. Section of fish skin. (From Ref. 1, with permission of the publisher.)

2. Mucus can provide protection to a fish while it is resting. Jakowska (Ref. 2) records Winn's description (Ref. 3) of certain species of parrot fish that envelop themselves in a translucent gelatinous cocoon of their own mucus when they rest in the dark. They break out of the cocoon with daylight. Jakowska states that "one of Hawaiian wrasses *Labroides phthirophagus* also forms a gelatinous cocoon like the scarids."

3. According to Jakowska, Hildemann (Ref. 4) states that the newly hatched young of the Amazonian discus fish (*Symphysodon discus*) feed from the skin of their living parents, evidently eating the parents' slime.

4. Slime is used by some fish as a means of defense. Stark (Ref. 5) calls attention to the fact that the slime of the spotted soapfish (*Rypticus saponaceus*) has a composition toxic to other fish. A predator that takes the small soapfish into its mouth must promptly spew it out.

5. The mucus layers protect some fish from bacterial and parasitic attack. As described by Jakowska, Nigrelli (Ref. 6) has demonstrated that "mucus from a small tropical marine teleost has antibiotic action against *Staphylococcus aureus* and *Pseudomonas pyocyanea*." Nigrelli also demonstrated the role of mucus in a fish's immunity to metazoan parasites.

6. It has long been a supposition of fishermen that the external mucus secretions of fish might have another important function—that of enabling them to "slip" through the water with relative ease. A number of investigators through the years have attempted to show this, but the results have been uniformly negative. The work described in the present report deals with that question: Does the slime of fish assist them in swimming?

Kempfe and Neu in 1932 (Ref. 7) and Richardson in 1926 (Ref. 8) conducted experiments with real fish and wooden models of fish. These investigations concluded that fish, slime or no slime, do not have a "drag" (water resistance) any lower than that of inanimate man-made objects of the same shape and size.

Gero in 1952 (Ref. 9) used a wooden aerodynamically streamlined body of revolution which he dropped through a vertical water tank. He states, "The model was first dropped dry, and a drag value was determined at terminal velocity. The mucus from a dogfish (*Amia calva*)<sup>1</sup> was then liberally applied to the model, and the drop was repeated. The application of the mucus rendered no reduction in drag, but there was a slight increase in the directional stability."

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<sup>1</sup>*Amia calva* is actually the bowfin. The term "dogfish" is sometimes incorrectly used to designate bowfins. The dogfish is actually a small species of shark, very much different from bowfins.



The work of all the above investigators seemed to be conclusive that slime does not lower the resistance of water to the motion of fish.

However, it is known that certain chemicals—particularly some artificial polymers when put into solution—can cause a reduction of turbulent drag. Toms (Ref. 10) found that methylmethacrylate when dissolved in the solvent monochlorobenzene would lower the turbulent friction of the solution. Hoyt and Fabula in 1964 (Ref. 11) and Hoyt and W. White in 1965 (Ref. 12) tested the slime of a sea fish and of a hagfish and found small drag reductions of 14.5% and 12.8%, respectively. Also Ripken and Pilch in 1964 (Ref. 13) reported that dogfish slime showed a drag reduction. These results revived the intuitive idea that the slime of fish may assist them in swimming.

Hagfish are not fish; they are scavengers, eel-shaped animals belonging to the class Cyclostomata, the lowest of living vertebrates, having no jaws, scales, or differentiated heads. Dogfish also are low on the evolutionary scale, having partly cartilaginous skeletons like the archaic sharks and lampreys, and are much as they were in the primeval Jurassic and lower Tertiary ages. Could it be that these ancient species were isolated examples and that the slime of the more “modern” and highly developed true fish does not reduce drag?

The writers studied the slime of some of the true fish, the Teleostei, the modern aquatic vertebrate “bony fish” proper, whose skeletons consist of actual bone rather than cartilage. Most of these fish have continued their evolutionary progress to the present age. The Teleostei include all but a few species of living fish.

The primary objective of the investigation was to determine if animal slime, particularly the slime of the true fish, possesses physical properties capable of altering the friction, or resistance, of flowing water. If such an effect actually exists, it would add significantly to our knowledge of hydrodynamics, and perhaps also to our understanding of the propulsion of fish. The experimental methods used and the measurements and observations made are described in this report. With the experimental evidence as a basis, the writers hypothesize, first, a relationship between slime and the life habits of aquatic animals and, second, the means by which slime aids fish to swim.

## METHOD OF OBTAINING SLIME

Natural fresh slime was obtained from the external body surfaces of different species of fish available in Southern California. The slime was taken not from dead fish, but from live, wild, healthy animals caught in their natural environment of stream, lake, or ocean waters. Also, the slime was tested in situ within minutes after

the live fish was taken from the water, to assure that no substantial decomposition, enzymic action, or bacterial attack (which acts rapidly on fish slime) had taken place.

Thus on expeditions into wilderness and ocean areas it was necessary to take along not only rods, reels, nets, lines, and other fisherman's equipment, but also the special testing instruments, associated laboratory apparatus, glass vessels, miscellaneous equipment, and an electrical power source for the instruments, and to have them at hand, set up, and ready in an operating state wherever the fish themselves were found and caught.

About 122 fish were captured, of 16 different species. Sixty of these were large enough to be tested, and successful experiments were conducted with 14 species of fish, plus 1 species of sea snail.

After each fish was caught, it was held in the air by the gills or jaws, tail down, to allow excess water to drain from its body for a period of 10 to 15 seconds. If at the end of that time the dripping was seen to be gelatinous, the live fish's body was gently wiped across the surface of a special smooth metal table. The slime adhering to the table was collected by a soft rubber blade and allowed to drip into a receptacle. If these operations were successful, about 1½ to 2½ cc of slime might be collected from a 13-inch fish. The operation must be done quickly, for the bodies and slime of most fish dry rapidly in air. In some instances, it was found possible, after removing the slime, to return the fish to its home in the waters where it would swim away, substantially unharmed.

After loose scales were carefully removed from the slime, the substance was diluted to various known concentrations with clean water from the fish's natural habitat. Within 5 minutes after the fish were removed from the water, testing of the samples was begun with a machine known as a rheometer.

## DESCRIPTION OF THE RHEOMETER

The rheometer can measure the turbulent frictional resistance of a slime solution, and enables one to compare its friction with that of plain water flowing at the same rate through the same instrument. Thus it was possible to determine whether slime had a greater or lesser resistance to flow than water.

The rheometer used for the slimes was originally designed to measure the friction of polymer solutions. The principle of operation and a prototype apparatus were first developed and described by J. W. Hoyt (Ref. 14) in his studies of the frictional properties of high polymer solutions.

The device used here in the study of fish slime is smaller and lighter than Hoyt's but is identical in its principle of operation. Figure 2 shows a schematic diagram of the machine illustrating its operation, and Fig. 3 shows it as it was finally redesigned by the writers.

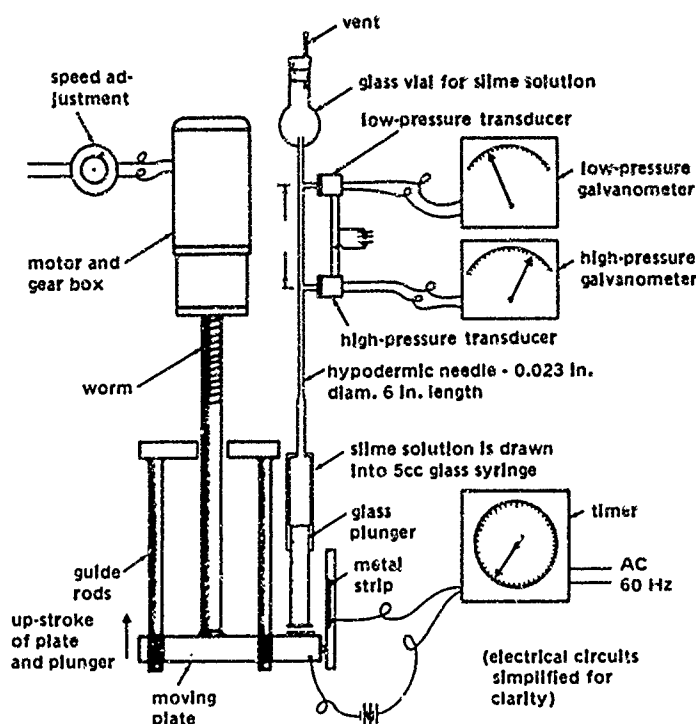


Figure 2. Schematic diagram of portable rheometer.

The slime sample is slowly drawn into a 5-cc medical syringe consisting of a glass cylinder and piston. A small electric motor drives the glass piston upward, forcing the solution through a 6-inch-long stainless steel hypodermic tube of 0.023 inch internal diameter. At two points 3 inches apart, the tube is pierced with small side outlets. The static pressure of the moving fluid is sensed at these two points by means of electrical pressure transducers whose faces are in direct contact with the pressures in the side outlets. The electrical signals are proportional to the pressures and can be read on two meters after steady-state flow conditions are reached. The fluid is discharged at the top of the tube in a vented glass receptacle. With this small rheometer, solution quantities as small as 5 cc can be tested.

Before a slime is tested, the machine is calibrated by running it with clean water from the particular fish's habitat, whether freshwater or seawater. The water

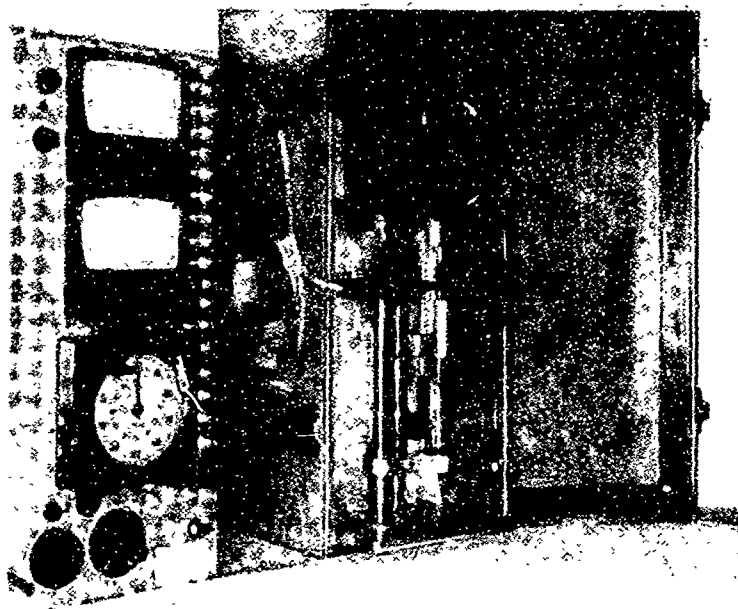


Figure 3. Portable rheometer and instruments.

pressures and their difference are noted. The time required for the piston to travel a fixed distance (0.9625 inch) is automatically read by an electrical timer to better than 0.01 second, thus establishing the piston speed.

The pressure readings of tests made with the fish slime are then compared with the readings taken with water. The comparison is made when the speed of the glass piston for both the slime tests and water tests is the same, thus assuring that the velocities of the fluids in the hypodermic tube are the same for both types of test.

The friction reduction (if any) is arrived at by the method used by Hoyt:

$$\text{Friction reduction} = 1 - \frac{(p_1 - p_2) \text{ for slime}}{(p_1 - p_2) \text{ for water}} \quad (1)$$

where  $p_1$  = static pressure at 1st measurement point

$p_2$  = static pressure at 2d measurement point

The drop of static pressure of a liquid flowing in a constant-diameter tube is directly proportional to the energy loss. Therefore, Eq. 1 gives a true measurement

of the reduction of friction as compared with water, if the flow velocity of the slime solution and that of the water are the same.

The instrument is designed so that turbulent flow is obtained in the tube. After the piston reaches equilibrium speed in its stroke, it will force a constant-flow velocity in the hypodermic tube of about 45 ft/sec. This corresponds to a pipe Reynolds number<sup>2</sup> of nearly 8000 (based on water). In smooth tubes, turbulent flow begins at pipe Reynolds numbers of 2000 to 4000. Thus the velocity of the fluid in the rheometer tube is sufficient to ensure a well-developed turbulent flow for water.

## SLIME OF FRESHWATER FISH

### Fish at Morris Dam

NUC has a laboratory at the site of Morris Dam Lake in the San Gabriel Mountains, north of Azusa, California. Small boats, docks, and other needed facilities, including 110-volt 60-Hz alternating current for the rheometer and its instruments, are available there. The instruments and other apparatus were set up conveniently about 70 feet from the shoreline. The lake possesses a variety of freshwater life. A number of fish were caught, but only one-third of them were large enough to undergo slime collection and tests.

The writers' experiments with the freshwater fish of this lake were successful. It was found that their slime is definitely capable of reducing the friction of water by surprisingly large amounts.

The slime of each species of fish will be discussed separately. Also, the ecology, the life habits, and the biological characteristics of the species will be described briefly for reasons to be explained in later sections of the report.

Smallmouth bass (*Micropterus dolomieu*). The smallmouth bass were the first to undergo tests in which all of the requirements were met: the fish were wild specimens, alive, healthy, and uninjured, and the slime was tested immediately and diluted to known concentrations. The results were most gratifying, for the slime of these fish reduced the turbulent friction of flowing water by amount as great as 62%.

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<sup>2</sup>Pipe Reynolds number =  $Vd/\nu$

where  $V$  = velocity of fluid, ft/sec

$d$  = internal diameter of tube, ft

$\nu$  = kinematic viscosity of water ( $1.09 \times 10^{-5}$  ft<sup>2</sup>/sec for water at 68° F)

These fish, ranging from 13 to 16½ inches long and from 1 pound to 2 pounds, 1 ounce, were caught in Morris Dam Lake on many different days, all giving consistent results. Figure 4 is a photograph of one of the fish tested.



Figure 4. Smallmouth bass.

The smallmouth bass belong to the sunfish family. They are a strong and fast fish. Even a 1 pounder will strike with considerable force and give the fisherman quite a fight. Their bodies are reasonably well streamlined hydrodynamically (Fig. 5), and they swim very rapidly, catching other fish such as bluegill and crappie for food.

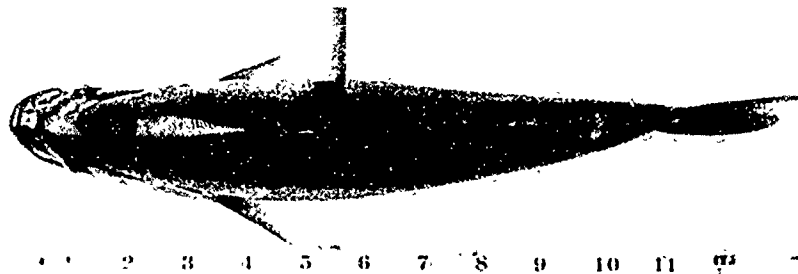


Figure 5. Top view of smallmouth bass.

The results for all the specimens of smallmouth bass tested are shown in Fig. 6, where the measured friction reductions are plotted versus the concentration of the fish's original slime when diluted in water. The data on these fish, taken from different individuals caught on different days, but all of the same species, form a reasonably consistent curve.

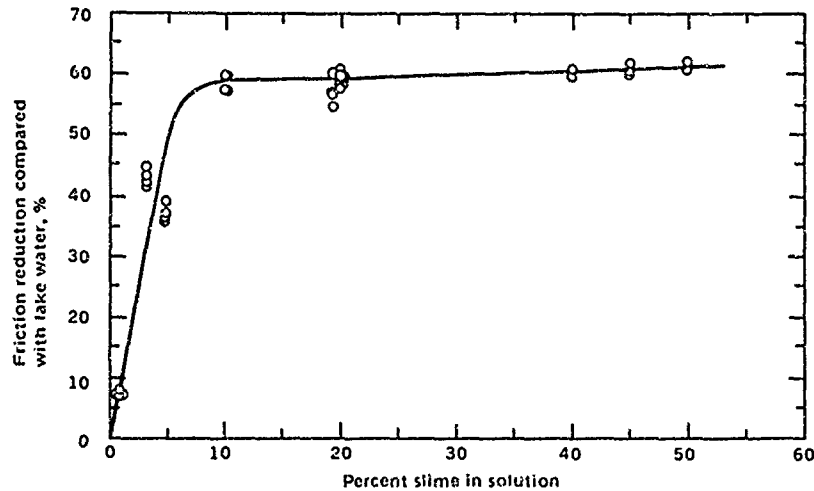


Figure 6. Slime effectiveness of smallmouth bass.

This slime attains a friction reduction of 62% at a 50% concentration (1/2 original slime plus 1/2 water). Friction reductions of 59.4% were still attained by solutions having only a 10% slime concentration; and reductions of 45% to 41% were measured at the low concentration of only 3.3% slime in water. The slime of smallmouth bass dissolves easily and quickly in water, and as can be seen, it is an effective friction-reducing agent.

An example of some of the primary test measurement data is shown in Fig. 7. This shows the measured differences of the two meter readings (corresponding to the pressure difference  $p_1 - p_2$ ) at the two measurement points in the hypodermic tube, plotted for slime and for water. The abscissa is the elapsed time (seconds) required for the steady portion of the piston stroke (0.9625 inch). The pressure differences of the slime solutions are very much less than those for plain water, when compared at the same elapsed time (equal flow velocities).

How much solid material is there in the slime of smallmouth bass? It was found that "original slime," or 100% fish slime as taken from the body of the fish, is itself composed mostly of water. Two samples of slime from this species were weighed, diluted with water, and then dried at room temperature (65°F to 75°F) under a vacuum for approximately 7 days. At the end of this time, the residues appeared as a very thin grayish white film left on the glass bottom. The residues were weighed on an analytical balance to better than 0.0005 gram. It is the writers' belief that the fish uses lake water to make its slime; therefore, a known correction for the amount

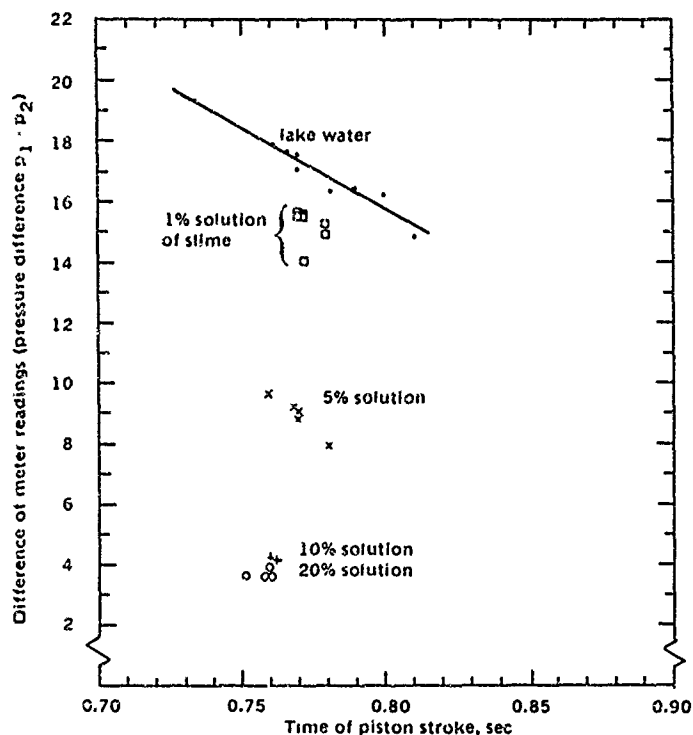


Figure 7. Example of test data for a 2-pound, 16½-inch-long smallmouth bass.

of solid minerals dissolved in the clean water of the lake was applied.<sup>3</sup> The results were as follows:

1st sample: Residue = 0.164% of original slime, by weight

2d sample: Residue = 0.143% of original slime, by weight

Average = 0.153% of original slime, by weight

It is suspected that the residues themselves, although apparently dry, still contained a substantial percentage of water captured molecularly as water of crystallization. It is estimated that this could be as much as 1/3 to 1/2 by weight. In these samples the residue was not heated to drive the captured water off.<sup>4</sup> Obviously the natural slime of this fish contains only a small amount of solid substances.

<sup>3</sup>According to the Chemistry Department of the Metropolitan Water District of Southern California, Morris Dam Lake, when clear, contains 191 parts per million of salts in the water.

<sup>4</sup>When slime samples were placed in a dry electric oven at 165°F to 170°F, the slime partially oxidized before drying, leaving a residue that was brown and sticky. The water could not be driven off by heat without oxidation and perhaps decomposition also taking place, thus making weight measurements useless when these higher temperatures were used.



The preceding facts, together with the results found on other species of fish, have enabled the writers to hypothesize the manner in which the fish uses the friction-reducing property and other properties of its slime to aid its swimming. This hypothesis will be set forth in the last section of the report.

**White Crappie (*Pomoxis annularis*).** The white crappie (Fig. 8) is also a member of the sunfish family, frequenting underwater weeds, brush, and holes. This is not a swift fish, but it can move quite suddenly and rapidly to escape an attacker.

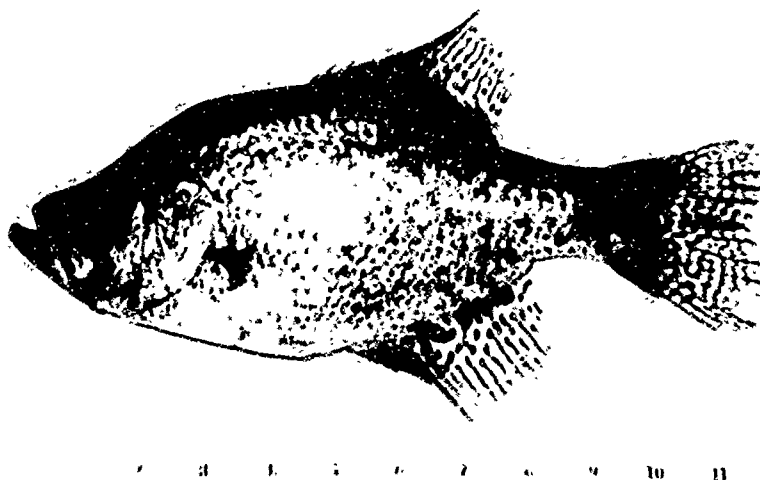


Figure 8. White crappie.

Friction reductions ranging up to 61.7% were obtained at a 20% concentration of white crappie slime in water. The curve of friction reduction versus percent slime in solution (Fig. 9) does not rise as rapidly at lower concentrations (5% and 10%) as does the slime of the smallmouth bass. But the maximum friction reduction of 61.7% is about the same as that of the bass.

Of considerable interest are the results on a sample of white crappie slime which could not be immediately tested. The sample was diluted to 3.3% concentration and had been exposed to ambient temperatures of 80°F to 90°F for approximately 3 hours before it could be measured. When the tests were made, this sample showed zero friction reduction. But when the slime of other white crappies was tested immediately after being removed from the fish, the 3.3% concentrations gave friction reductions of 24% to 25%.

The 3-hour-old slime possibly lost its effectiveness due to the action of enzymes or bacteria which almost immediately attack fish slime at those temperatures.

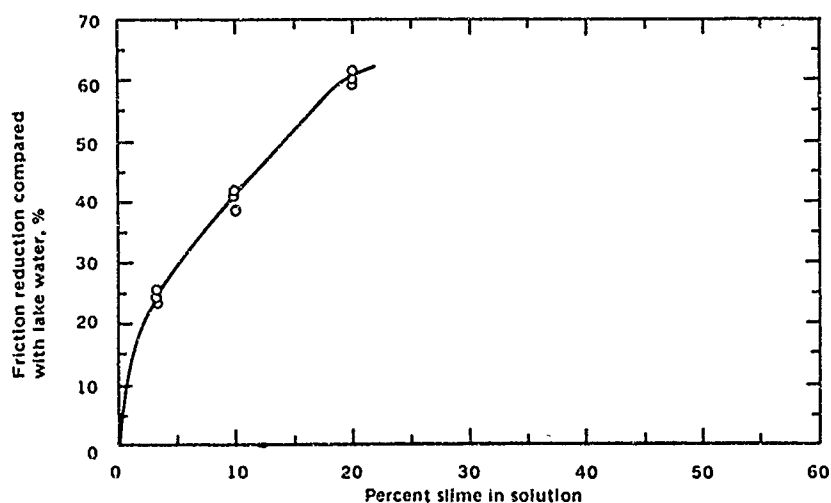


Figure 9. Slime effectiveness of white crappie.

Bluegill (*Lepomis macrochirus*). Morris Dam Lake abounds in 6-to-8-ounce bluegill (Fig. 10). These lively little fish are also members of the sunfish family. Their smaller individuals serve as prey for the smallmouth bass, for though they can dart about and maneuver swiftly, they are not fast enough to escape the "express train" attack of the bass. Bluegills feed on small crustaceans, if available, and on other minute water life and plants.



Figure 10. Bluegill.

It required a catch of 7 bluegill to collect 4.3 grams of slime. Figure 11 shows the data on the slime. The curve of friction reduction looks very similar to that for the white crappie, but at the lower concentrations it does not rise as rapidly as that

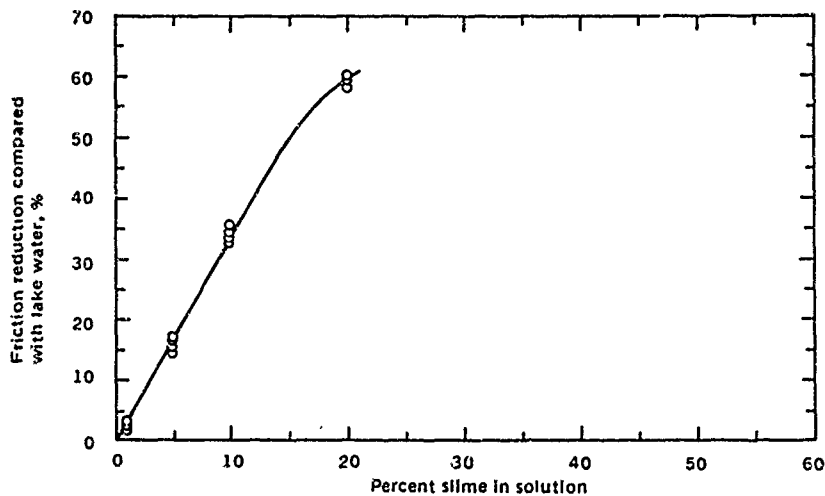


Figure 11. Slime effectiveness of bluegill.

for the crappie, while neither of these rise as rapidly as the curve for smallmouth bass slime. At a higher concentration of 20% in water, the friction reductions obtained were as high as 60.1%, nearly as high as the two preceding species.

#### Sierra Nevada Species

The work was carried to the Sierra Nevada Mountains of California, where the wary and swift trout, a member of the family Salmonidae, are found in their natural environment.

Trout, related to salmon, are renowned as a food and game fish. Some varieties, such as the cutthroat trout and the steelhead trout, sometimes migrate to sea, as do the salmon. Fishermen at sea often confuse steelhead trout with young silver salmon, they appear so much alike.

In general, however, trout prefer the fresh cold water of high-altitude mountain lakes and streams, and spawn only there. Their food consists largely of insects, small crustaceans if available, and smaller fish. The Dolly Varden trout (*Salvelinus malma*) is so voracious that it will feed on other small trout of the same species. Trout strike suddenly and, for their size, give the fisherman a hard, forceful fight. They will leap out of the water to catch a flying insect. Once hooked, if this fish manages to break free, it becomes extremely wary and difficult to catch.

At least four distinct varieties (of which three species could be tested) were caught in the high-altitude wilderness regions of the Sierra.

To test these species, the rheometer, its instruments, glassware, and other associated apparatus were organized into a mobile laboratory in an automobile (Fig. 12). In addition, the following electrical equipment was also installed in the car: a group of heavy storage batteries to supply 30 volts direct current, a battery charger, cables, and an electrical inverter (needed to invert the direct current to 110-volt, 60-Hz alternating current required by the rheometer and its instruments). This, with the addition of a collapsible wire aquarium (fish jail), made possible the testing of fish slime in the wilderness.

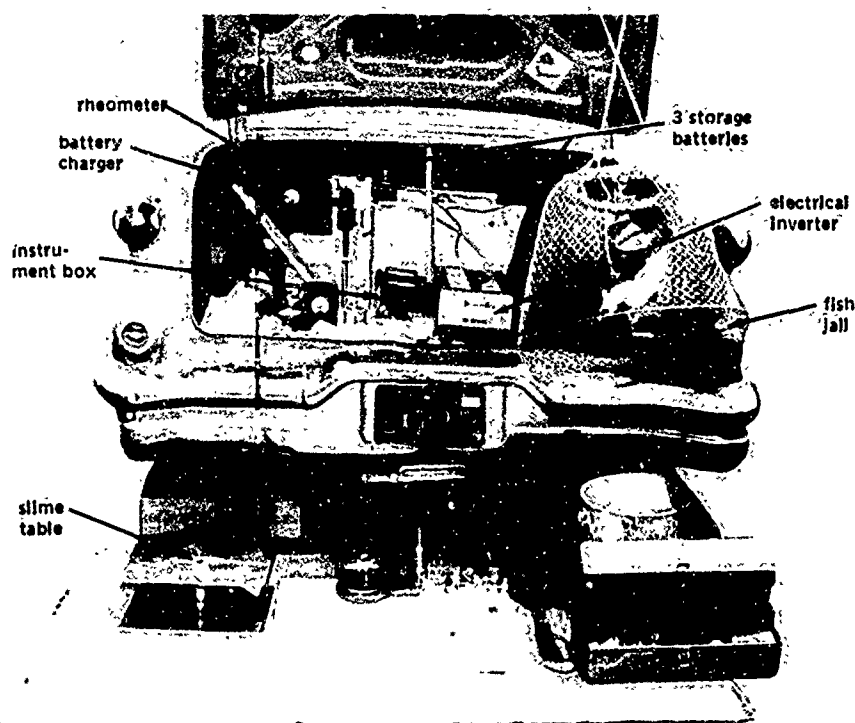


Figure 12. Mobile laboratory for wilderness testing.

Rainbow Trout, Lundy Creek and Lundy Lake (*Salmo gairdnerii*). Young rainbow trout about 6 inches long were caught in Lundy Creek, but they yielded so little slime that tests could not be made. At Lake Lundy, however, rainbow trout 9 inches long were caught. These also did not have a great deal of slime, four of them yielding about 4 grams of slime, which seemed quite thin, even though the fish were well drained. The tests showed only a moderate 20.5% friction reduction at 50% concentration in water (Fig. 13). This was unexpectedly low. It was found that these fish had white flesh, which indicates that they were quite young.

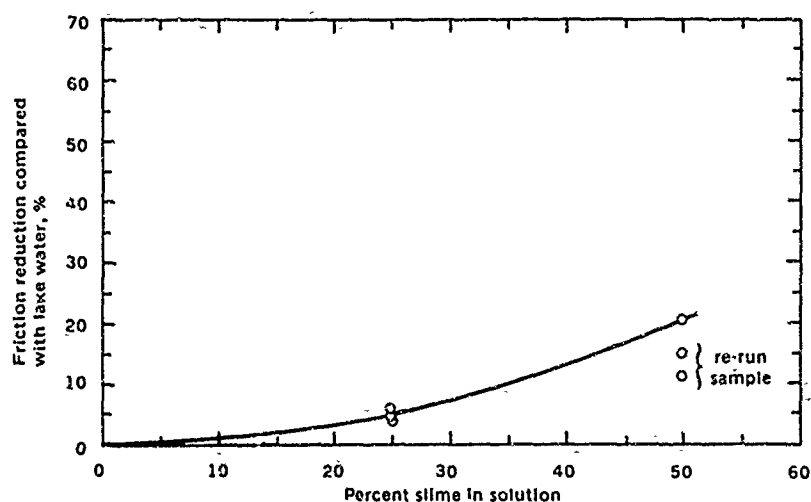


Figure 13. Slime effectiveness of Lake Lundy rainbow trout.

**Speckled Rainbow Trout, Rush Creek (*Salmo gairdnerii*).** A number of lively beautiful speckled rainbows about 11 inches long were taken in Rush Creek, a swiftly running stream in the vicinity of Silver Lake (see Fig. 14). Although these fish appeared to be the same species as the Lundy specimens, the slime of the Rush Creek fish had a consistency thicker than that of the Lundy trout. The slime dissolved easily, and at 50% concentration in water gave a maximum 61.8% friction reduction, which was considered excellent. Diluted to 25% concentration, a 30.1% friction decrease was obtained (Fig. 15). The flesh of these fish, which apparently were the same species as the Lake Lundy trout, was pink, not white, indicating that they were older than the Lundy specimens. The data suggest that larger fish of the same species possibly generate a thicker and more effective slime. Thus, the size of fish may also be a factor in the amount and effectiveness of their slime.

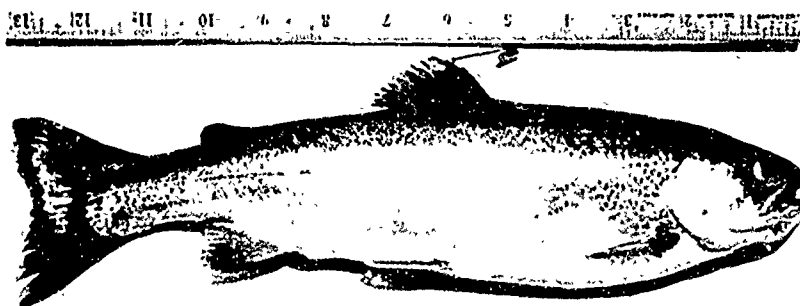


Figure 14. Speckled rainbow trout.

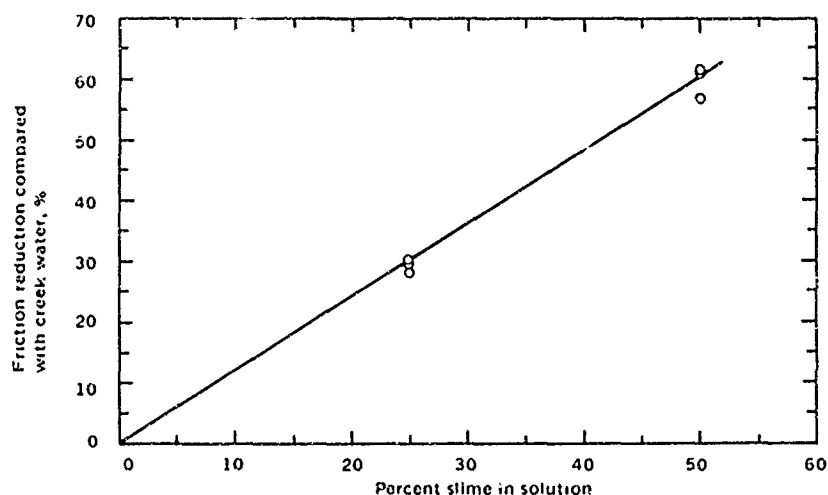


Figure 15. Slime effectiveness of speckled rainbow trout.

**Kamloops Rainbow Trout, Grant Lake (*Salmo gairdnerii kamloops*).** A 13-inch blue and silvery colored Kamloops rainbow trout was caught in Grant Lake (Fig. 16). This fish provided 5.5 grams of clean slime, thicker than that of either the Lundy or Rush Creek fish. Though thick, the slime of this fish dissolved very easily and gave a 62% maximum friction reduction at 50% concentration in water (Fig. 17). But at greater dilutions, the friction-reduction properties were better than those from the fish at either Lundy or Rush Creek. The flesh of this fish was also pink. Other 12-inch rainbows were caught at Grant Lake at 9 p.m. one evening, but attempts at testing them failed due to lack of light.



Figure 16. Kamloops rainbow trout.

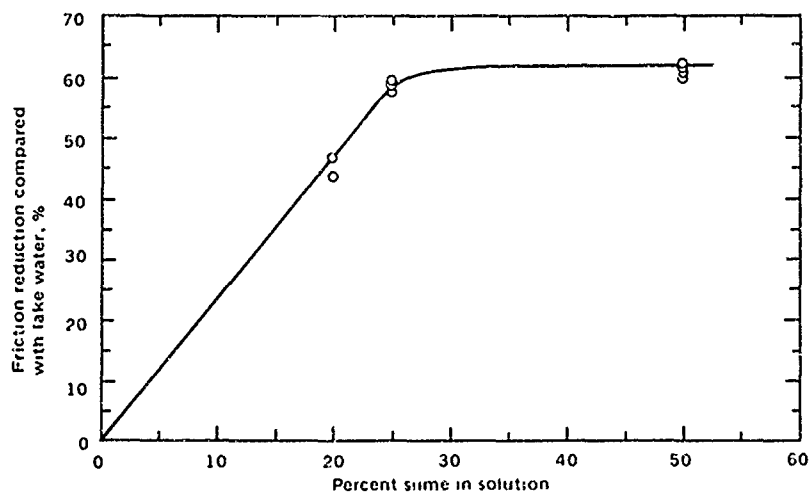


Figure 17. Slime effectiveness of Kamloops rainbow trout.

German Brown Trout, Silver Lake (*Salmo trutta*). A 13-inch-long representative of the wary and difficult to catch German brown trout was caught in Silver Lake (Fig. 18). The thick slime of this animal dissolved easily and showed an excellent friction reduction of 63.2% at only 25% concentration in water, and a 37.8% friction reduction at 10% concentration (Fig. 19). This slime was found to be more effective than that of the previous two species of trout at lower concentrations. It also had good resistance to breakdown: four trials with the same 25% concentration sample lowered the friction reduction from 63.2% to 57.8%. The slime of the German brown trout seemed the most effective of all the trout slime tested.



Figure 18. German brown trout.

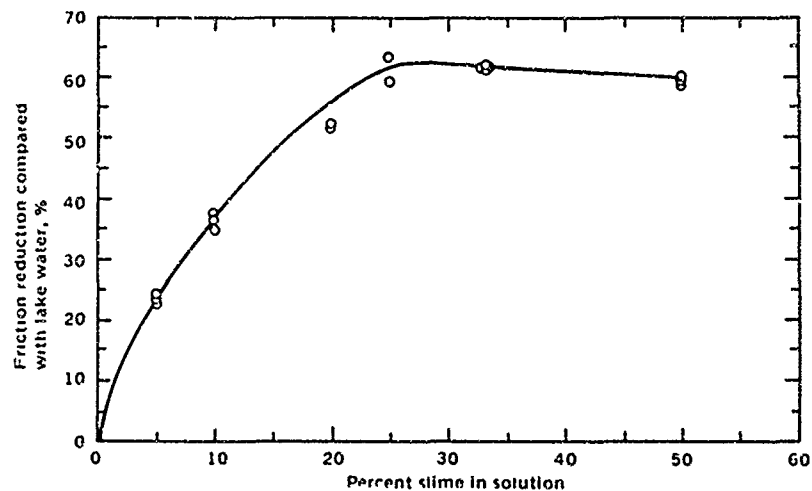


Figure 19. Slime effectiveness of German brown trout.

Although all the above Sierra trout are not of identical species, they are of the same family, Salmonidae, and it is interesting to compare the curves of their slime effectiveness. The 6-inch trout had too small an amount of slime to furnish a test. The 9-inch rainbow trout gave moderate results; the 11-inch speckled rainbow trout gave a more effective slime; the 13-inch Kamloops rainbow trout and 13-inch German brown trout also gave effective slime. The effectiveness of the slime of this family apparently increases with the size or the age of the fish, particularly at the lower concentrations.

**Sierra Golden Trout (*Salmo aguabonita*).** On a private trip into the Sierra Nevada Mountains one of the authors, Neri E. Cornford, climbed to lakes and streams at altitudes of about 12,000 feet. There he fished and caught 8-to-12-inch-long specimens of the golden trout. The rheometer and its heavy electrical supply could not be carried to these remote areas, accessible only on foot, and so the slime was not tested. But the slime of this species was observed to cover the fish copiously and to be exceedingly thick. The waters in which this fish lives are



extremely cold, flowing directly from the melting snows of the Sierra. Perhaps the heat insulation afforded by the thick coat of slime may help this species to survive in the frigid waters.

Breakdown of Slime Properties

**Fish at Morris Dam.** In some of the tests the same sample of slime solution was run through the rheometer a number of times. In general, each additional operation with the same sample caused a lowering of its ability to reduce friction. Figure 20 shows this trend. Each run through the rheometer included two passages through the 6-inch-long, 0.023-inch-internal-diameter tube. The first passage is slow, when the solution is drawn down by hand into the glass syringe. The second occurs as the motor drives the fluid upward rapidly through the tube, and measurements are taken.

The slime of the smallmouth bass is seen to be quite resistant to breakdown of friction properties at the high concentration of 45%; in 17 runs the friction reduction was lowered from about 60% to 51%. The more dilute 5% solution seems to break down more rapidly, as indicated by the slopes of the lines. The figure also shows some data for the breakdown of white crappie slime.

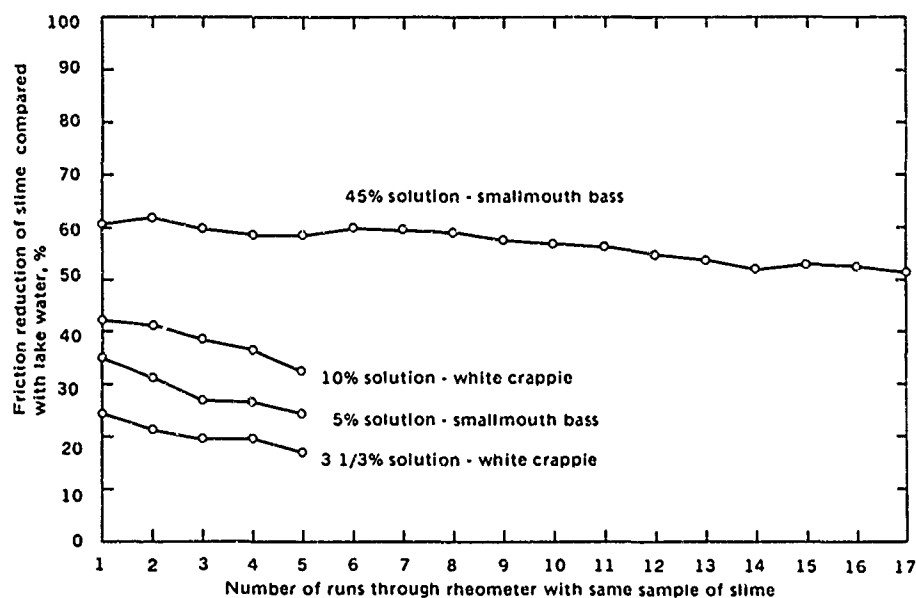


Figure 20. Resistance of slimes of fish at Morris Dam to breakdown of effectiveness.

Sierra Nevada Species. Much the same lowering of antifrictional properties was observed in the trout slime as was found in the smallmouth bass and crappie slime when repeated runs were made with the same sample. Again, the higher concentration solutions resisted deterioration better than the lower concentrations. This is well shown by the 50% solution line for Kamloops rainbow trout in Fig. 21. After the seventh trial with the same sample, the friction reduction was still quite high at 58.8%.

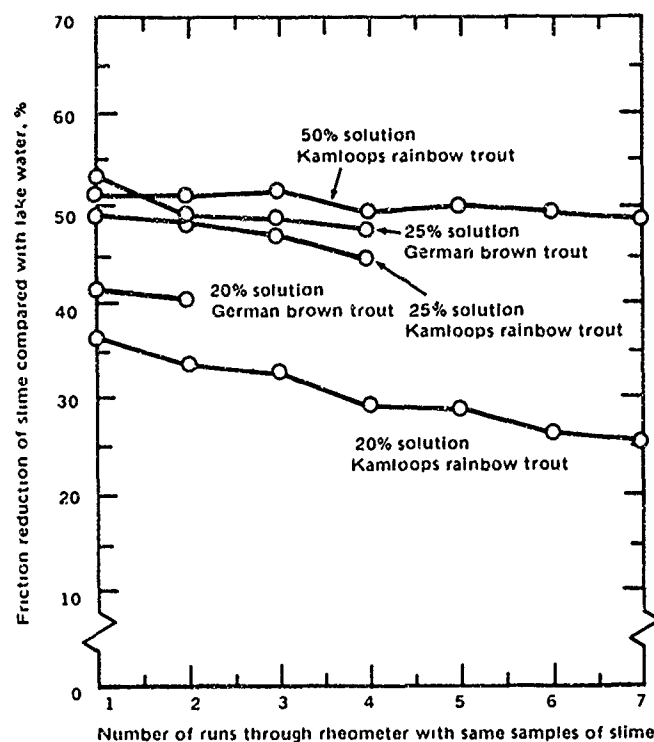


Figure 21. Resistance of slime of Sierra Nevada species to breakdown of effectiveness.

## SLIME OF MARINE ANIMALS

In order to investigate the slime of marine animals, the writers went to sea in Pacific Ocean waters from 1 to 30 miles off the coasts of Los Angeles and Catalina Island.

The boat was specially fitted with two large tanks in which seawater was constantly circulated and replenished by means of pumps. One tank was used to keep alive a supply of anchovies which were used as bait. (These would live for about

6 hours.) The other tank was large enough to allow the fish which were caught to swim around.

The tank enabled the writers to keep the fish alive and healthy for several hours until they could be tested. When caught, the fish were not gaffed (which seriously injures them), but instead were brought up out of the water by means of a large net and were quickly transferred to the tank.

The slime of the ocean fish, like that of the freshwater animals, displayed a marked ability to reduce the friction of turbulent, flowing water. Friction reductions of as high as 65.9% were measured for one species.

However, there were some outstanding and surprising exceptions. In one species no friction reduction could be measured at all. In another species some reductions were evident but only at high concentrations. In yet another species it was even difficult to dissolve the slime in seawater.

#### California Halibut (*Paralichthys californicus*)

The habit of the halibut (Fig. 22) is to rest flat on the bottom. A master of camouflage, it changes the colors and patterns of its upper side to match the background. Flipping sand over itself until it can hardly be seen, it lies in ambush with only its bulging eyes protruding from the sand. If a fish wanders nearby, the halibut suddenly rises from its ambush and darts out swiftly to capture the prey. Hellyer (Ref. 15) says: "Actually this fish is lightning quick, capable of flashing through the water with incredible rapidity when feeding or frightened."



Figure 22. California halibut.

The writers caught halibut up to 21 inches long in the horseshoe kelp beds off the coast of Los Angeles. These fish all had their eyes on the left side, which was the colored side, indicating them to be a warm water fish.

The slime of these fish was very thick and viscid, and initially seemed to resist dissolving. However, with a little mechanical agitation it suddenly and easily dissolved in seawater. Remarkably, it retained its thickness even when diluted; 50% solutions repeatedly plugged the rheometer and could not be tested; 25% solutions and lower concentrations would go through the machine; but even when diluted to 5% this slime was still of a remarkably thick and sticky consistency.

The data obtained from two of the larger specimens are shown in Fig. 23. A friction reduction as high as 60.9% was obtained with only a 5% solution; and a reduction of 54.3% was measured with only a 2.5% solution. The curve rises very steeply. Unlike other curves of slime performance, the halibut curve seems to reach a peak at 5% solution, then drops off slightly to about a 55% friction reduction at 2.5% solution. Because of the initial steepness of the curve, halibut slime is believed to be a highly effective friction reducer.

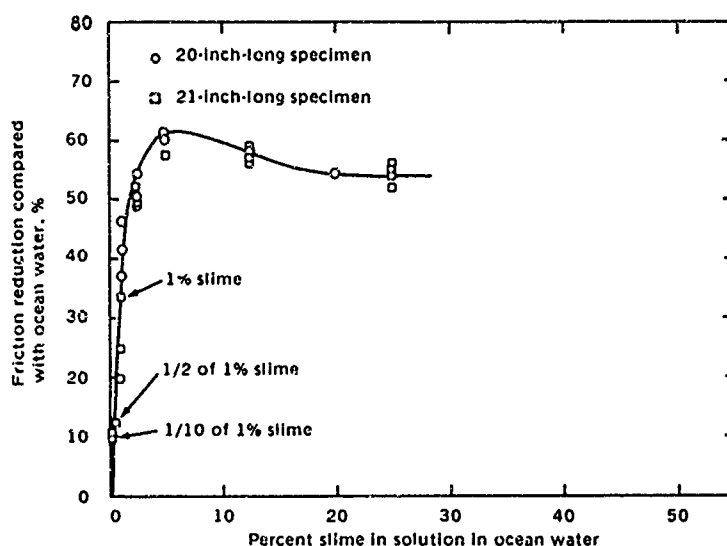


Figure 23. Slime effectiveness of California halibut.

#### Pacific Mackerel (*Scomber japonicus*)

The Pacific mackerel (Fig. 24) is abundant on the Pacific coast and is a member of the Scombriform family, all of whose members possess beautifully streamlined bodies. Mackerel are a swift fish and put up a hard fight for their size.



Figure 24. Pacific mackerel.

The slime of a first group of mackerel, taken from specimens 15 to 16½ inches long, was thick, but it was unlike those of other fish tested, for it tended to curd, and resisted going into solution. However, if stirred vigorously, it abruptly dissolved in seawater. Some curds would persist, however, and sometimes plugged the slender tube of the rheometer. Fine scales came off this fish very easily and had to be laboriously removed from the collected slime.

The results with this species were puzzling. The slime of the first group of fish was tested within 10 minutes of capture. At 20% concentration in seawater, friction reductions of only 10.3% to 17.4% were obtained. With 10% concentration, only 3% to 4.8% friction reductions were measured. The writers decided to check this species again.

On a succeeding day Pacific mackerel of about the same size were caught, and a 16.7% solution was tested within 4 minutes after capture. This yielded 14.2% to 15.4% friction reductions—in line with the previous tests.

On a third day a catch of the same species and about the same size was made. Tests were successfully performed with a 50% solution, which yielded friction reductions from 48.5% to 56.9%. Figure 25 shows the data.

The curve displays the slime effectiveness of all three catches. Clearly the slime of this species is not too effective at the lower concentrations. The curve is not similar to those of other fish, for it requires a 50% concentration to approach the friction reductions obtained with the slime of other species.

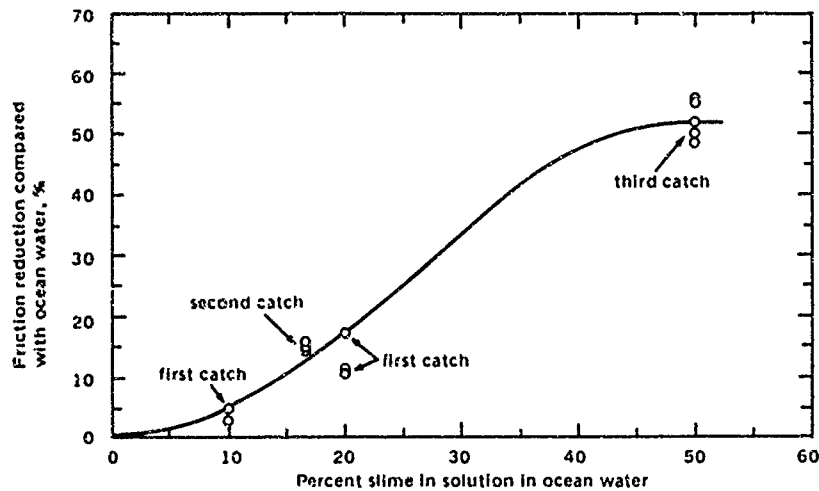


Figure 25. Slime effectiveness of Pacific mackerel.

#### Calico Kelp Bass (*Paralabrax clathratus*)

The sea bass belong to the family Serranidae, of which about 58 North American species are known.

A 17-inch calico kelp bass (Fig. 26) was caught in Horseshoe Kelp, a large submerged kelp bed about 15 miles offshore Long Beach harbor. A size of 17 inches, indicating an age of about 9 years, is fairly large for this species. These fish seldom

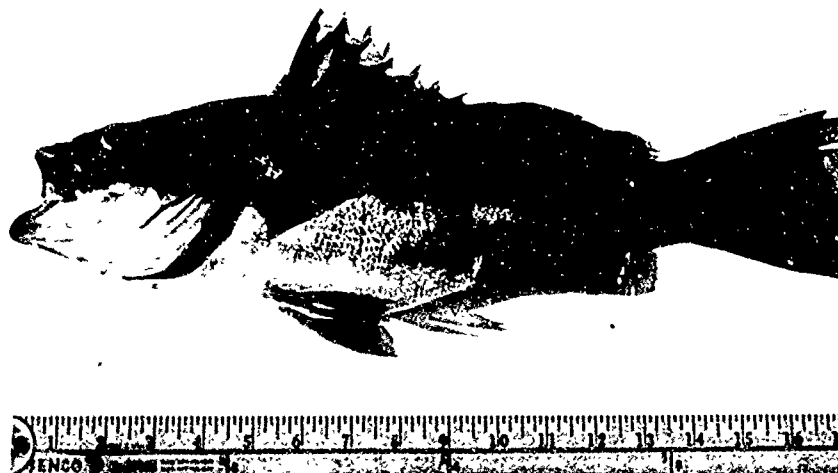


Figure 26. Calico kelp bass.

move far from their home in the kelp beds where they easily find their food of shrimplike crustaceans, anchovies, and other small fish.

Though little is known of their speed, the calico kelp bass give a good fight and in all probability are fairly fast, since the older fish catch and eat many smaller fish.

The slime of this fish dissolved quite readily in seawater when stirred and was diluted to concentrations of 50%, 25%, 12.5%, and 6.25%.

A maximum friction reduction of 58.7% was obtained with the 25% solution, and a reduction of 57.2% was measured with the 50% solution. This is a fairly good slime, with the curve of Fig. 27 progressing smoothly and showing a much greater effectiveness at lower concentrations than mackerel slime, as well as a greater maximum friction reduction.

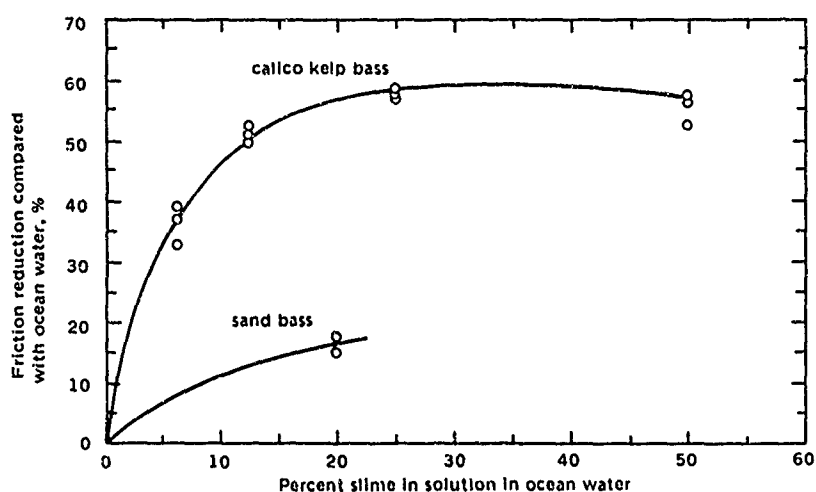


Figure 27. Slime effectiveness of calico kelp bass and sand bass.

#### Sand Bass (*Paralabrax nebulifer*)

Several specimens of sand bass (Fig. 28), also of the family Serranidae, were caught in the kelp beds. This species is similar to but not quite like the calico kelp bass. Sand bass are only fair to poor as fighters.

Although there was a fair amount of slime on this fish, it was unlike that of the calico, for its slime did not dissolve readily in seawater, even with stirring, and showed a tendency to curd. Because of the curding, only one solution strength of 20% concentration could be tested. The results gave a 14.8% to 17.4% friction

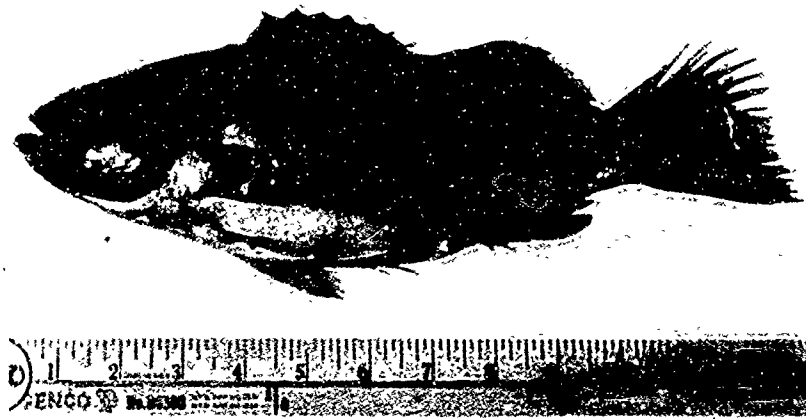


Figure 28. Sand bass (dorsal fin is partially collapsed).

reduction. While this is appreciable, the slime evidently is not as effective as that of the calico kelp bass. Figure 27 shows the data compared with the data for the calico kelp bass.

#### Bronze Spotted Rockfish (*Sebastes gilli*)

Several bright orange-red and bronze spotted rockfish (Fig. 29), sometimes confused with red snappers, were caught at a depth of 350 to 400 feet.

There are 50 or more known species of rockfish, many of which live solely in deep waters as adults. Their heads and fins are often armored with sharp spines, and they have the interesting distinction of being viviparous.



Figure 29. Bronze spotted rockfish.



These bronze spotted fish evidently cannot stand a rapid decrease of pressure when brought to the surface by line and hook, and due to the writers' inexperience were dead and puffed out on surfacing. Other fish were being caught at the same time and since they were alive were tested first. The slime from the dead rockfish was by then too old for valid tests.

#### White Croaker (*Genyonemus lineatus*)

A number of white croakers of the family Sciaenidae were caught near shore on the bottom sands off Santa Cruz, California. The specimens obtained were 9 inches long, but they were not young fish since in this species 2 or 3 year olds are only about 6 inches long. These fish do not put up a hard fight. They are good bait stealers and are bottom feeders in sandy shallow water. They are not considered to be a fast swimming fish, and their diet includes mostly small squid, shrimp, worms, octopi, small crabs and fish, and other slow-moving, easy-to-catch animals.

The slime, collected immediately after the fish were removed from the sea, was exceedingly thick. Four specimens yielded 5.3 grams. But this substance surprisingly would not dissolve in seawater even with vigorous stirring; instead it coagulated into large lumps. Even after remaining immersed in seawater in a flask for several days, it remained as lumpy blobs. Consequently, it could not be tested in the rheometer effectively.

Since this slime did not readily dissolve in water, it probably does not create any substantial friction reduction in seawater.

#### Pacific Barracuda (*Sphyræna argéntia*)

The barracuda is sometimes called the tiger of the sea, for it is both ferocious and fast. In the Atlantic Ocean, the great barracuda (*Sphyræna barracuda*) possesses large caninelike razor-sharp overlapping teeth and has been known to attack and severely injure man. Gero (Ref. 9) measured the speed of several great barracuda that were hooked and swimming, dragging a fishing line through the water and also powering a speed measurement and drag device by means of the line. He recorded speeds of 40 ft/sec (27.3 mph) for a barracuda that was overcoming the extra resistance of the line and also the device. This fish, therefore, should be able to exceed that speed when running completely free.

On the Pacific coast a less vicious and smaller species exists, the Pacific barracuda (*Sphyræna argéntia*). This animal has a form that seems primarily designed for speed. It is slender and aerodynamically shaped, as can be seen in the photograph of one of those caught and tested by the authors (Fig. 30). In hydrodynamic terms,

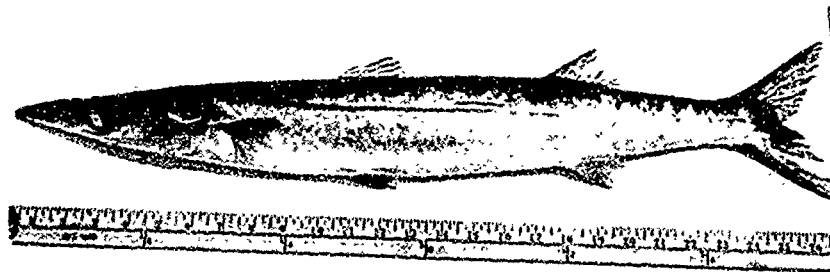


Figure 30. Pacific barracuda.

a fish of this shape should have very little form drag, or resistance, for the configuration of its body resembles that of a supersonic aircraft.

The fresh slime of the Pacific barracuda proved to be the most effective friction reducer of all the fish species tested. Eleven of this species were caught on different days, varying from 26 to 31 inches long. The slime was tested immediately after being removed from the live fish.

The slime dissolved readily in seawater, was not lumpy or curdy, and did not tend to plug the slender rheometer tube, even at a thick 50% concentration. A maximum friction reduction of 65.9% was obtained at a concentration of only 5% slime in seawater. This is the largest friction reduction obtained of all the fish tested. When diluted down to only 1.5% concentration, friction reductions of 61% to 63% were still maintained. The data are shown in Fig. 31. The excellent effectiveness of this slime may be noted by the swift rise of the curve at low concentrations.

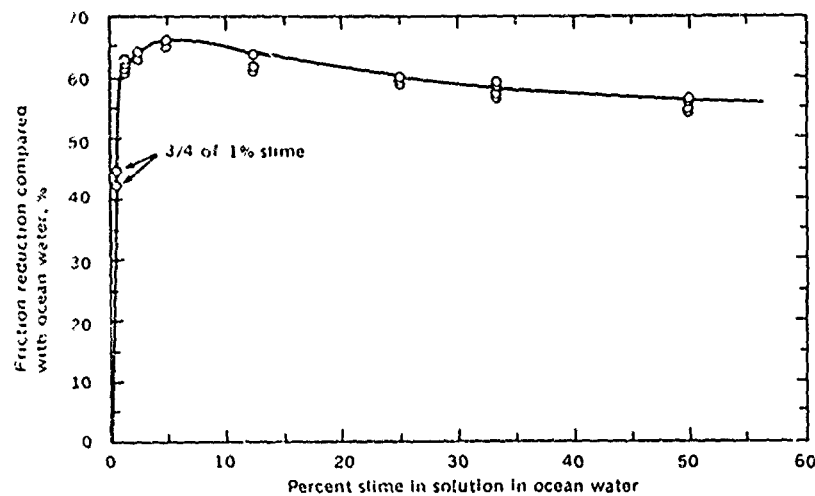


Figure 31. Slime effectiveness of Pacific barracuda.

Of interest were tests made on nonfresh slime from this same species. The slime was 2½ to 3 hours old (after removal from the live fish) before the tests could be performed. The results showed a maximum friction reduction of 50% to 51.4% at a 5% concentration and a 35% to 37% friction reduction at a 50% concentration. The nonfresh slime was rapidly losing its effectiveness.

#### California Bonito (*Sarda chiliensis*)

California bonito (Fig. 32) are fish belonging to the same family as the tunas (Thunnidae) and are closely related to the Scombridae family, which comprises the mackerel and a few kindred forms.

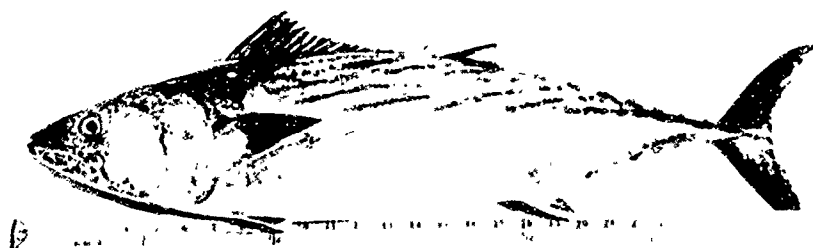


Figure 32. California bonito.

Bonito swim in schools several miles off the Pacific coast, approaching land only in search of food or for spawning. They are most abundant in regions south of Santa Monica Bay. They are powerful fighters and are believed to be extremely fast, particularly since they can catch and eat mackerel, which is itself a fast and maneuverable swimmer. The diet of a bonito also consists of menhaden, anchovies, and squid. The colors of a bonito immediately after it has been removed from the water are brilliant iridescent blues and whites. Its fine individual scales are practically indistinguishable by eye and form a smooth skin. Its body is a hydrodynamically streamlined shape which seems built for speed.

The first fish of this species caught, 29 inches long, supplied a light gray slime. Unlike the slime of other fish, it seemed very thin, although the fish was well drained of excess water. It was found possible to run this slime through the rheometer at a 100% concentration (no dilution), as well as diluted with seawater. An unexpected result was obtained: the slime showed very little ability to reduce friction.

At a 100% concentration the highest friction reduction obtained was 6.4%. When the slime was diluted with seawater, values ranging from a 3.5% friction

reduction to zero were obtained. Some of the measurements showed up to a 3% increase of friction at 12.5% and lower concentrations.

These unlikely results prompted the writers to try a check. A week later, several other bonito of the same species were caught. The fish, about 25 inches long, were thoroughly drained of water, and the slime was quickly collected from the live struggling fish and tested within a few minutes. The results were the same. The highest friction reduction measured was 3.9% at a 50% concentration. Also values of zero were obtained at lower concentrations, including some data points which again showed a slight friction increase. The data are shown in Fig. 33, which gives the measurements of both catches.

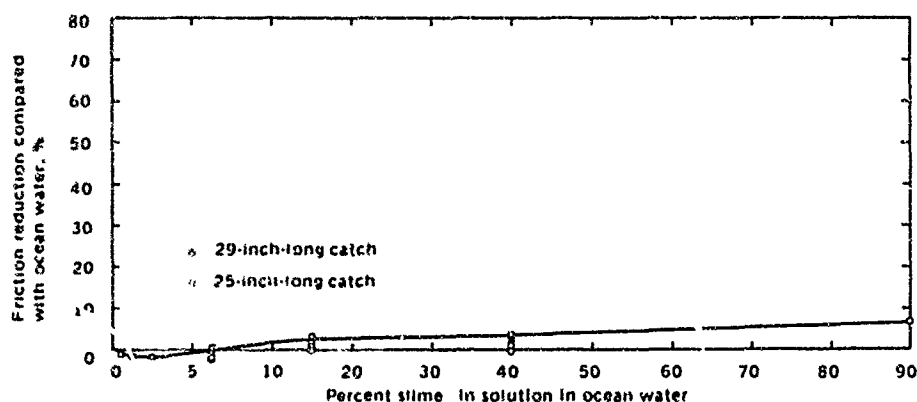


Figure 33 Slime effectiveness of California bonito.

The skin of the bonito feels smooth and slick to the touch, but not slimy as do other fish. An attempt was made to collect slime with the fingers and with the soft rubber blade by running them firmly along the sides of the fish. The substance collected in this way showed the same results as above in a few spot checks. Apparently, then, the bonito produces a slime that is not effective in reducing friction, a surprising and puzzling result, for this is a swift swimmer.

#### Nut-Brown Cowry (*Cypraea (Zonaria) spadicea*)

For purposes of comparison, a study of the slime of a sea animal that is not a fish was made possible by Mr. Herbert Summers.<sup>5</sup> While skindiving off the coast of the Palos Verdes Peninsula of California, he collected a number of cowries and later brought them alive to NUC.

<sup>5</sup> Formerly of the Naval Ordnance Test Station

A cowry is a snail-like animal--a mollusc of the class Gastropoda, the order Pectinibranchia, and the genus *Cypraeidae*. The species caught by Mr. Summers was the nut-brown cowry (*Cypraea (Zonaria) spadicea*). This animal creeps along and carries a 2-inch-long smooth brown and white shell. Its head protrudes from the shell with two tentacles, on the ends of which are the eyes. Unlike ordinary garden snails, it wraps a red and white fleshy mantle partly around the outer surface of its shell, making a colorful appearance.

Cowries live on or near rocks and ledges on the ocean shores, feeding on small sea anemones, sponges, algae, and eggs of other snails. Like most molluscs it can cling tenaciously to objects with its foot, making the suction force quite effective by means of its mucus. Many molluscs use their mucus to entrap food and nutrient particles, such as decaying plant material, tiny animals, other edible matter drifting about them in the water, and algae and slimes growing on rocks (Ref. 16). The mollusc eats its own slime with whatever food has adhered to it.

The cowries were reluctant to give up their slime. It could not be scraped from their foot or head, for they would immediately retract them into their shell. Prodding the animal inside its shell produced no slime. Finally, the vessel containing them in seawater was put in a refrigerator for 2 days at 57°F. The cowries then exuded small globs of thick slime which floated freely below the surface of the seawater, showing that the slime's density was the same as that of the water. These globs were carefully removed and tested. The 50% slime concentration (with seawater) was so thick and sticky that it plugged the rheometer. Solutions of 25% concentration and less were workable, however, and dissolved without curdling.

This slime was found to be definitely capable of producing friction reductions in flowing water. The data are shown in Fig. 34. A friction reduction of 63.1% was

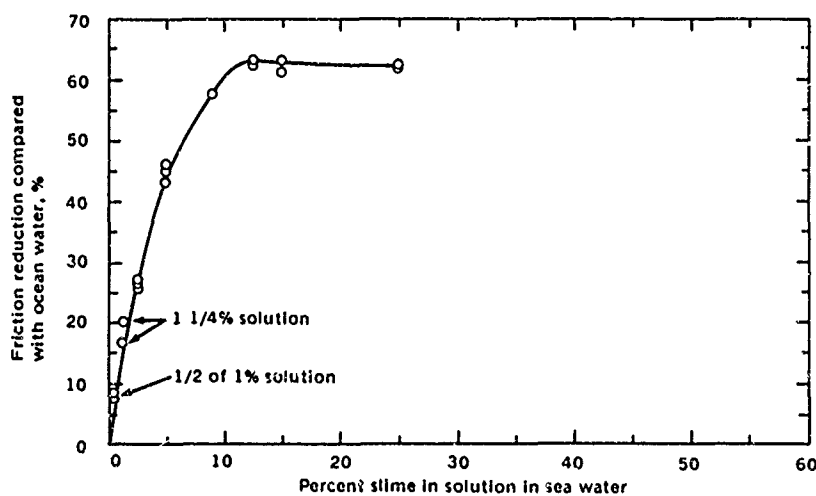


Figure 34. Slime effectiveness of nut-brown cowries.

obtained at a 12.5% concentration; a 57.5% reduction was obtained at a 9% concentration; and a 27% reduction was obtained at a 2.5% concentration. This is a fairly effective slime, comparing favorably with the fish slime tested.

The results with this mollusc indicate again that animals do not utilize their slime for one purpose alone. It is quite possible that the cowry mucus serves to insulate the animal from cold, acts as a low friction lubricant between its hard shell and the moving tissues, and particularly enables the muscular foot wetted with the slime to cling firmly to a surface by suction. It may be that slime serves such functions for all molluscs.

#### RELATIONSHIP BETWEEN AQUATIC ANIMAL SLIME AND TAXONOMICAL CLASSIFICATION

Living creatures are biologically related to each other according to the physiology of their bodies, and have been carefully classified by science on this basis. Is there a relationship between the properties of fish slime and the biological classification of the animal?

In Table 1 the various species observed have been organized by taxonomical classification. Each animal is identified as to its species, family, order, class, superclass, and phylum, and the biological relationships between the species may be seen. A few observations of other workers have been added.

Thus, from the table it can be seen that the white croaker is related to the speckled rainbow trout, since they both descend from a common ancestor—the Isospondyli, fish whose fins do not have spiny rays. Likewise, although barracuda and halibut are of different families and even of different orders (as much unlike as any two fish can be), they are both teleosts. They both have strong skeletons and vertebrae of real bone. On the other hand, the hagfish and the cowry are not fish at all. In fact, the cowry is not even a chordate.

Several additional observations may be made by referring to Table 1 and to the data recorded in this report.

1. Slime effectiveness is definitely related to the taxonomical classification of species. That is, individual fish of the same species have slime with the same properties. If this were not true, the measurements made on many different individual fish of the same species would show no consistency and would not fall into reasonably smooth curves, as do those for *Micropterus dolomieu*, *Lepomis machrochirus*, *Paralichthys californicus*, *Sphyræna argentea*, and others.

Phylum			Class		Order	Family	Species
Phylum Chordata, the chordate animals.	Group Chranaiata, the vertebrates. All animals with craniums, vertebrae, brains.  Gnathostomata All animals with jaws and paired appendages.	FISH Water-breathing, swimming vertebrate animals, with paired fins, gills, scales. Class Osteichthyes	Superclass Pisces	Teleostei  The true fish, with vertebrae and skeletons of true bones rather than cartilage. High on scale of evolution.	Percomorphi Perchlike fish, with spiny fins.	Centrarchidae Freshwater sunfish and bass	<i>Micropterus do</i> <i>Pomoxis annul</i> <i>Lepomis machr</i>
						Thunnidae	<i>Sarda chiliensis</i>
						Scombridae	<i>Scomber japon</i>
						Sphyraenidae	<i>Sphyraena arge</i>
						Serranidae	<i>Paralabrax clati</i> <i>Paralabrax nebi</i>
						Scorpaenidae	<i>Sebastodes gilli</i>
					Isospondyli Fins without spiny rays.	Salmonidae Salmonlike fish	<i>Salmo gairdneri</i> <i>Salmo gairdneri</i> <i>Salmo gairdneri</i> <i>kamloops</i> <i>Salmo trutta</i> <i>Salmo aguaboni</i>
						Sciaenidae Croakers	<i>Genyonemus li</i>
					----	----	----
					Heterosomata The flat fish, mi- grating eyes, undu- lates up and down.	Hippoglossoides	<i>Paralichthys cal</i>
				Paleopterygii Ancient fish, arrested development, partially cartilaginous skeleton.	Protospondyli	Amidae	<i>Amia calva</i>
				----	----	----	----
	Agnatha No true jaws. Not fish.		Cyclostomata Lowest of the vertebrates; suctorial mouth.		Myxinoidea	Slime eels and hagfish	<i>Polistotrema ste</i> (monoecious)
	Mollusca		Gastropoda Univalves, whelks, snails, limpets.		Pectinibranchia	Cypraeidae	<i>Cypraea (Zonar</i> <i>spadicea</i> <i>Bulla gouldiana</i>

\*Reluctance is defined as that property of slime that keeps it from entering into solution with water until mechanically agitated. 0 indicates little or no reluctance, 10 indicates great reluctance.

Table 1. Biological Classification of Animals Whose Slimes Have Been Measured

Species	English Name	Habitat	Max. Friction Reduction of Slime Compared With Water	Friction Reduction at Low Slime Concentration	Solubility of Slime in Water	Reluctance of Slime*
<i>Micropterus dolomieu</i>	smallmouth bass	fresh-	62% at 50% conc. in water	59.4% at 10% conc. in water	very good	2
<i>Pomoxis annularis</i>	white crappie	water	61.7% at 20% conc. in water	41% at 10% conc. in water	good	2
<i>Lepomis macrochirus</i>	bluegill	lakes	60.1% at 20% conc. in water	34% at 10% conc. in water	good	2
<i>Sarda chiliensis</i>	California bonito	sea	6.4% at 100% conc. in water	-3% at 12.5% conc. in water	very good	0
<i>Scomber japonicus</i>	Pacific mackerel	sea	56.9% at 50% conc. in water	4.8% at 10% conc. in water	fair	8
<i>Sphyræna argenta</i>	Pacific barracuda	sea	65.9% at 5% conc. in water	62.9% at 1.5% conc. in water	very good	3
<i>Paralabrax clathratus</i>	calico kelp bass	sea	58.7% at 25% conc. in water	39.2% at 6.25% conc. in water	good	3
<i>Paralabrax nebulifer</i>	sand bass	sea	17.4% at 20% conc. in water	----	poor	7
<i>Sebastes gilli</i>	bronze spotted rockfish	sea	----	----	----	--
<i>Salmo gairdnerii</i>	speckled rainbow trout	fresh-	61.8% at 50% conc. in water	30.1% at 25% conc. in water	very good	2
<i>Salmo gairdnerii lundy</i>	Lake Lundy rainbow trout	water	20.5% at 50% conc. in water	5.8% at 25% conc. in water	very good	1
<i>Salmo gairdnerii kamloops</i>	Kamloops rainbow trout	streams and lakes	62% at 50% conc. in water	46.7% at 20% conc. in water	very good	2
<i>Salmo trutta</i>	German brown trout		63.2% at 25% conc. in water	37.8% at 10% conc. in water	very good	2
<i>Salmo gairdnerii</i>	Sierra golden trout		----	----	----	--
<i>Genyonemus lineatus</i>	white croaker	sea	could not be run through rheometer		very poor	10
----	sea fish	sea	14.5% at 6 times the unknown conc.	1.5% at an unknown conc.	----	--
<i>Paralichthys californicus</i>	California halibut	sea	60.9% at 5% conc. in water	54.3% at 2.5 conc. in water	very good	4
<i>Amia calva</i>	bow fin (misnomer dogfish)	fresh-	zero (unknown freshness of slime)	zero (unknown freshness of slime)	unrecorded	--
		water lakes				
----	dogfish	sea	est. 55% at unknown conc.	est. 25% at 1/3 of unknown conc.	unrecorded	--
<i>Polistotrema stautti</i> (monoecious animal)	California hagfish (not a fish) (cartilaginous skeleton)	sea	12.8% at unknown conc. mechanically homogenized with water	10.9% at unknown conc.	poor	10
<i>Cypraea (Zonaria) spadicea</i> <i>Bulla gouldiana</i>	nut-brown cowry (sea snail) bubble shell snail (sea snail)	sea, rocky shores, sea, estuaries	63.1% at 12.5% conc. in water  12% at 3 times unknown conc.	46% at 5% conc. in water  9.1% at unknown conc.	very good  ----	5  --



measured

of er	Friction Reduction at Low Slime Concentration	Solubility of Slime in Water	Reluctance of Slime*	Effectiveness as Friction Reducer	Consistency of 100% Slime Taken From Animal	Investigator
	59.4% at 10% conc. in water	very good	2	very good	moderately thick, like mayonnaise	Rosen and Cornford
	41% at 10% conc. in water	good	2	very good	moderately thick, like mayonnaise	Rosen and Cornford
	34% at 10% conc. in water	good	2	very good	slightly thinner than mayonnaise	Rosen and Cornford
	-3% at 12.5% conc. in water	very good	0	very poor	very thin and watery	Rosen and Cornford
	4.8% at 10% conc. in water	fair	8	poor	extremely thick, congeals in small curds	Rosen and Cornford
	62.9% at 1.5% conc. in water	very good	3	excellent—best slime measured	moderately thick, like mayonnaise	Rosen and Cornford
	39.2% at 6.25% conc. in water	good	3	good	moderately thick, like mayonnaise;	Rosen and Cornford
	---	poor	7	poor	tended to small flaky curds thick; tended to small curds	Rosen and Cornford
	---	---	--	--	thick	Rosen and Cornford
	30.1% at 25% conc. in water	very good	2	fair	moderately thick, like mayonnaise	Rosen and Cornford
	5.8% at 25% conc. in water	very good	1	poor	thinner than mayonnaise	Rosen and Cornford
	46.7% at 20% conc. in water	very good	2	good	moderately thick, like mayonnaise	Rosen and Cornford
	37.8% at 10% conc. in water	very good	2	very good	slightly thicker than mayonnaise	Rosen and Cornford
	---	---	--	--	very thick and copious on fish	Cornford
run through rheometer		very poor	10	ineffective	extremely thick; congealed in large curds	Rosen and Cornford
	1.5% at an unknown conc.	---	--	--	slime was 1 day old	Hoyt and Fabula
	54.3% at 2.5 conc. in water	very good	4	excellent - 2d best slime measured	100% slime very thick and gooey (5% solution thick, like mayon- naise)	Rosen and Cornford
	zero (unknown freshness of slime)	unrecorded	--	ineffective	unrecorded	Gero
	est. 25% at 1/3 of unknown conc.	unrecorded	--	good	stringy	Ripken and Pilch
	10.9% at unknown conc.	poor	10	poor	very thick and copious; formed tenacious gelatinous mass	Hoyt and White
	46% at 5% conc. in water	very good	5	very good	moderately thick, similar to mayonnaise	Rosen and Cornford
	9.1% at unknown conc.	---	--	poor	---	Hoyt and Irving H. Scribner

In Table 2 the species which have been discussed are listed in the order of their slime effectiveness. The order cannot be exact, but a rough pattern can be discerned. Figures 35 and 36 are presented as a further aid in comparing the effectiveness of the slimes of the freshwater and marine fish caught.

Table 2. Approximate Order of Slime Effectiveness\*

Animal	Environment	Speed of locomotion	Comments
1. Pacific barracuda	Sea	Very fast sustained speed	Predator, catches fast fish
2. California halibut	Sea	Fast	Predator
3. Nut-brown cowry	Sea	Very slow	Mucus lubricates and traps food
4. Smallmouth bass	Freshwater	Fast sustained speed	Predator
5. Calico kelp bass	Sea	Fast	Large adults catch smaller fish
6. White crappie	Freshwater	Fast in short spurts	Catches and eats smaller fish
7. German brown trout	Freshwater	Fast	Catches small fish and insects
8. Bluegill	Freshwater	Moderate speed in short spurts	Caught by smallmouth bass
9. Kamloops rainbow trout	Freshwater	Fast sustained speed	Catches small fish and insects
10. Speckled rainbow trout	Freshwater	Fast sustained speed	Were not fully adult fish
11. Pacific mackerel	Sea	Very fast sustained speed	Swims in fast schools
12. Sand bass	Sea	Moderate speed	Eats small fish
13. Lake Lundy rainbow trout	Freshwater	Moderate speed	Were young fish
14. California bonito	Sea	Very fast sustained speed	Catches many smaller fish
15. California hagfish (not a fish)	Sea	Slow	Parasitic scavenger, needs external lubrication
16. Bubble shell snail	Sea	Slow	Mucus lubricates and traps food
17. White croaker	Sea	Slow	Eats worms, crabs, shrimp

\*The animals are arranged in the approximate order of the friction-reducing effectiveness of their slime (in 25% concentrations or less): no. 1 has the most effective slime, no. 17 the least effective.

The Pacific barracuda is at the top of Table 2, having the most effective slime as a friction reducer. This corresponds with the high speed that its sibling species the great barracuda (*Sphyræna barracuda*) can attain (27.3 mph as recorded in Ref. 9). The Pacific barracuda can possibly attain or exceed this. The "supersonic" shape of

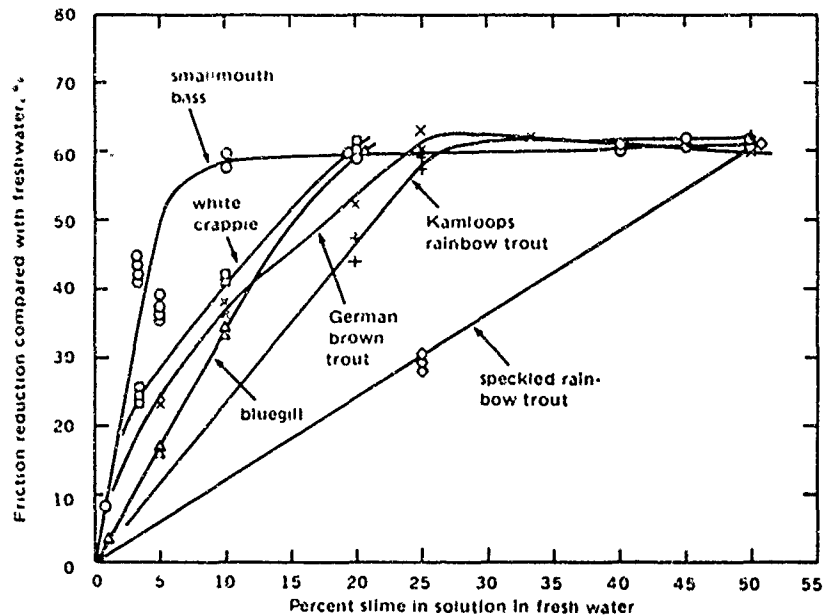


Figure 35. Friction reduction of slimes of freshwater fish when dissolved in freshwater in various concentrations.

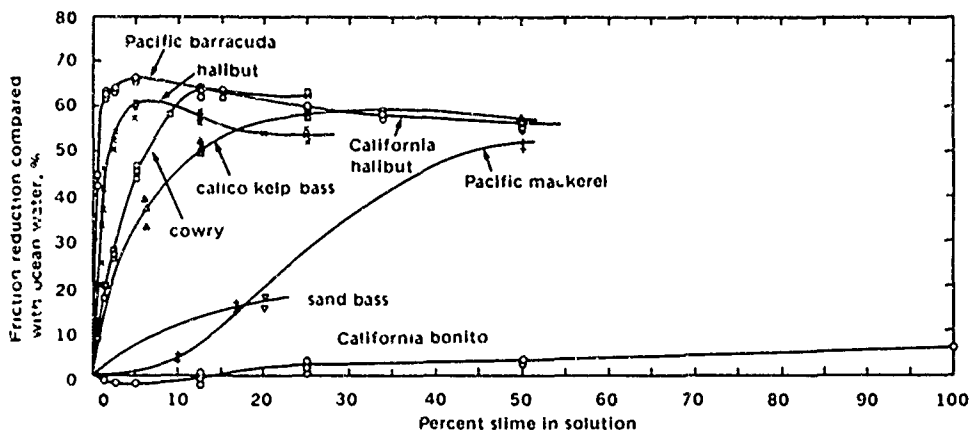


Figure 36. Friction reduction of slimes of seawater fish when dissolved in ocean water in various concentrations.

the Pacific barracuda is obviously adapted for a minimum hydrodynamic form drag. This animal preys on and eats only other fish, not slow animals like crustaceans or molluscs nor immobile plant food. The writers have not been able to find any record of the remains of a barracuda having been found in the stomach of another species of aquatic animal. Nature has designed this fish for a high velocity and has appropriately given properties to its slime that assist the characteristic of high speed.

The California halibut, next on Table 2, has excellent slime. This corresponds with its habit of lying in wait, flat, motionless, and camouflaged on the bottom, and suddenly making an incredibly fast lunge of some length to catch an unwary fish. For this it needs a minimum water resistance which its slime helps it to attain.

The nut-brown cowry is certainly not a fast animal. Its need is not for speed, but as a fairly mobile mollusc bearing a shell, it needs the best of lubrication. It seems to fulfill this need by having an excellent slime capable of reducing to a minimum friction between its constantly moving body tissues and the hard shell, as it crawls along or withdraws quickly into the shell for protection.

The smallmouth bass (next on the list) is a swift swimmer and a hard striker. It lives in the same warm water lakes as bluegill and crappie, catching and eating these smaller species and thus being ecologically dependent upon them. This corresponds well with properties of its slime, which is considerably superior as a friction reducer to that of the bluegill or crappie. The bluegill feeds on slow or immobile food such as small crustaceans, worms, and plants. It is not streamlined to any great extent and does not as a habit swim long runs rapidly. In keeping with its poor hydrodynamic shape and its feeding habits, its slime is not as effective as that of the smallmouth bass.

The German brown trout is a swift hard swimmer and possesses a fairly well streamlined body. Bluegill are far from streamlined, and so it is no surprise that the slime of the German brown trout was measured to be more effective than that of the bluegill at lower concentrations.

However, the other members of the trout family which were measured did not have as good a slime as crappie or bluegill—an apparent contradiction. Perhaps this is due to the previously noted observation that younger, smaller trout have less effective slime than older individuals of the same species. The Kamloops rainbow trout was larger than the speckled rainbow (Rush Creek) and had better slime, but was probably not old for this species. Kamloops trout have been caught (on rare occasions) as heavy as 30 pounds. The slime from a 30-pound Kamloops rainbow or speckled rainbow will most probably be an effective friction reducer.

The calico kelp bass of the size tested prey upon and eat the smaller fish which abound in kelp beds. Correspondingly, the measurements show a fairly good slime for this fish. The sand bass is not considered a fast fish or a good fighter. The measurements, in keeping with this, show the slime to have only a fair to poor friction-reducing ability.

The California hagfish has no need for speed, being a parasite and scavenger. According to Hoyt and White (Ref. 12) the hagfish slime was so thick that it formed cohesive masses of jell and could not be tested until it was homogenized with water by a mechanical blender. Its slime, as might be expected, is a poor water flow friction reducer. This corresponds with the hagfish's lack of need for speed. It also

corresponds with its habit of burrowing and sometimes burying itself within the carcass of a dead fish and eating it inside out. The copious jell-like slime completely around its body seems to be an appropriate lubricant for this purpose.

The white croaker is a feeder on slow sea life found on sandy shallow bottoms, such as worms, shrimp, and small squid. It, therefore, has little need for speed. Correspondingly its thick slime, which tends to curd, seems insoluble in seawater and is unlikely to produce a reduction of water friction. Its slime serves other purposes for the animal.

There are two anomalies in Table 2 which seem to be outstanding exceptions to the writer's hypothesis: the slime of the Pacific mackerel and the California bonito.

The Pacific mackerel is known to be a very fast swimmer, and to correspond with this, its body is well streamlined. Yet its slime at low concentrations is a poor water friction reducer. A water friction reduction up to 56.9% was obtained, but only at the high concentration of one part slime to one part water. This does not correspond with the mackerel's speed. Could it be that this species is capable of generating huge quantities of slime to mix one to one with the water flowing over its body? It does not seem likely.

The California bonito is the most outstanding exception yet found. This fish is known as an extremely fast swimmer, being able to catch and eat almost every smaller species of fish even catching and feeding upon the swift mackerel itself. It is a beautiful fish and its body shape, corresponding with its swiftness, is an almost hydrodynamically perfect streamlined form for low resistance to the flow of water. Yet the substance covering its body does not seem to be a "slimy" slime similar to that on other fish and was capable of producing no more than 6.4% friction reduction at 100% concentration. This could hardly be an aid to its swimming.

The Pacific mackerel and the California bonito belong to closely related families, the Scombridae and Thunnidae. Their body shapes and fin arrangement, including their characteristic small rear finlets, are very much alike and are sometimes described as the Scombriform type of body. These two fish evidently do not depend on their slime to aid their motion through the water. And yet they rank among the swifter swimmers in the ocean particularly the bonito. Their swimming speed must be attained in other ways.

It must be realized, as previously mentioned, that in addition to aiding a fish's locomotion, slime fulfills other functions for the animal.

## HYPOTHESES OF FISH SLIME AS AN AID TO SWIMMING

The old intuitive supposition that the slime of fish assists them to swim more rapidly can be considered now to be true for many fish, if we accept the following reasoning.

We have seen that fish slime (and other marine animal slime) when artificially dissolved in water does indeed lower the turbulent flow friction by large amounts. The basic reason for lowered friction is not yet clear, but by measurement it actually occurs—a fact that must be accepted. It is possible that fish slime contains long-chained, linear thread-like molecules of very high molecular weight characteristics which Hoyt and Fabula (Ref. 11) found in synthetic and plant substances that reduced water friction.

But even accepting the fact of the lowered friction of slime in an artificially dissolved solution flowing through an inanimate mechanical instrument, this does not in itself answer the whole question with regard to fish. Exactly *what is the process or action* between the fish, the water, and the slime which would enable the animal to use the above property to aid swimming? Also, what are the quantities involved? Can a fish produce enough slime to make its swimming substantially easier?

### Effective Quantity of Slime

Measurements showed that the natural thick slime taken from the scales of the smallmouth bass was only 0.153% solid substances by weight, the remainder being water. The hydraulic tests also showed that a 3.3% solution of the natural slime in water was able to produce a 45% friction reduction. Combining these two measurements:

$$\frac{0.153}{100} \times \frac{3.3}{100} = 0.0000505$$

Thus by measurement, only 50 ppm of the fish's organic substances are needed in water to create a solution that will reduce water friction by 45%.

Now, if as previously noted, the apparently dry residue of the slime contained an appreciable amount of captured water of crystallization (lacking direct measurement, this could be estimated at 1/3 to 1/2 by weight), then the smallmouth bass needs to supply only 25 to 33 ppm of its own organic substances to decrease water friction by 45%.

It is believed that the natural slime of the Pacific barracuda contains roughly about the same amount of organic material as that of the smallmouth bass (0.153%). Measurements of the Pacific barracuda slime showed a 44.5% friction reduction at the very low concentration of only 3/4 of 1% of this slime in water, and a 62.9% reduction at 1.5% concentration.

Crudely assuming water of crystallization as possibly 1/2 by weight:

$$\frac{0.153}{100} \times \frac{1}{2} \times \frac{3}{4} \times \frac{1}{100} = 0.00000573$$

$$\frac{0.153}{100} \times \frac{1}{2} \times \frac{1.5}{100} = 0.0000115$$

Thus the Pacific barracuda needs to supply only about 5.7 ppm of its own organic substances to the water to decrease friction by 44.5%. Or it need supply only about 11.5 ppm of its own organic substance to decrease friction by 62.9%.

These amounts are small indeed. We must also realize that a fish needs to expend this small amount only during the relatively short intervals of high speed required to catch another fish for food, or when it is itself in danger and must escape. For the greater balance of time most fish move only slowly and do not need to expend slime. For these reasons, and on the basis of the measurements, it is believed that fish are fully capable of producing a sufficient quantity of slime to effectively reduce their own friction with the water.

### Reluctance

The process by which the writers hypothesize that fish are enabled to swim more easily by their slime is described in the following way:

The mucus glands of the fish (Fig. 1) secrete specialized organic protein substances manufactured by the fish's own tissues. When these substances are mixed with body fluids a thick slime concentrate is formed which is excreted by the glands through ducts. These glands cover most of the fish's body, and the jelly-like concentrate finds its way between the scales, lubricating them. The concentrate is finally diluted with free seawater to form "fish slime," which covers the entire body of the animal.

During the course of their investigation the writers noticed that all the fish slime obtained had a curious reluctance to go into solution with water. To make the various solutions which were tested required some degree of mechanical stirring before the slime would abruptly dissolve in water.

Many of the slimes would not dilute well merely upon being in static contact with water, but upon stirring would go into solution easily. This property of slime we shall term its "reluctance." If we desire, we may give any slime a number which might describe this property on the arbitrary scale of 0 through 10. Thus, a slime with a very low reluctance of 1 would require little or no mechanical action to dissolve it. A slime with a reluctance of 5 might be quite resistant to going into solution with static water, but when mechanically stirred could have a high solubility and dissolve easily. A slime with a reluctance of 10 would show great resistance to being dissolved by static water and would not dissolve even with vigorous mechanical stirring. The writers have assigned arbitrarily estimated reluctance values to the slimes measured, these numbers appearing on Table 1. This property of reluctance is useful to the fish in the process next described.

### **Fish-Slime Reaction**

If the fish is moving slowly, the boundary layer water (those layers of fluid lying next to the fish's scales) may flow smoothly—or indeed be in the laminar flow state. Under such a condition, the water will not effectively dissolve away the fish's coat of slime because of the slime's reluctance to go into solution. If the fish swims more rapidly, however, there will be a point at which the boundary layer will break into small-scale turbulent flow. At this point, the turbulence of the water itself will overcome the reluctance of the slime to dissolve. The turbulence will supply a mechanical mixing action which will scour off some slime, dissolve it, and create a dilute solution in the turbulent water. Once the slime is in solution, turbulence is suppressed and lowered fluid friction with the scales of the fish is obtained. This action is illustrated in the Frontispiece.

Thus the very act of turbulent flow automatically produces a slime solution at the exact location where it is most needed, and does not produce it where it is not needed. As the fish swims faster, more and more of its body becomes enveloped with a slime-water boundary layer which lowers the resistance of the water (drag) to the fish's motion. The writers believe that by means of sensors underlying its scales the fish is able to feel the local areas where turbulence occurs in the boundary layer, and that the mucus glands only in those particular areas are then stimulated to produce additional slime concentrate as rapidly as it is used. Such action must, of course, be involuntary.



It is not contended that a slime solution will prevent the formation of large-scale organized vortices (large with respect to the fish's body) such as those which fish generate at the sides of their bodies when they swim (Rosen, Ref. 17). However, it is believed that the numerous small vortices which are thought by many to be characteristic of turbulent boundary layers are suppressed and dampened out on the fish's surface in an automatic fashion. By this hypothesis the turbulence itself produces its own suppression, this being made possible by the twin phenomena of slime reluctance and the friction reduction of fish slime solutions.

Thus to outline the essence of the hypothesis:

1. Measurements show that the quantity of slime-producing substances needed to substantially lower water friction around a fish is exceedingly small, and fish should be able to produce what is necessary.
2. The property of reluctance of fish slime and the mechanical action of turbulent flow make it possible for fish to create slime solutions in the boundary layer water around their bodies only at the points where needed and only when the fish desires to swim more rapidly. This action is fully automatic. The faster the fish swims, the larger is the surface area of the animal that is enveloped by a boundary layer of slime solution, and also, the more concentrated that solution becomes.
3. The property of fish slime to greatly reduce the turbulent friction of water (as proven by this work) when only very small amounts of the fish's organic slime substances are dissolved in the water enables the fish to swim more rapidly than otherwise. The faster the fish swims, the more effective its boundary layer becomes in reducing friction.

Thus, fish accomplish their natural act of swimming by taking advantage of several phenomena, not merely one. Those of which we may now say we have a modest understanding are:

1. The unique system of mathematically organized large vortices which fish generate about their bodies and which assist them in their propulsion (Rosen, Ref. 17).
2. The properties of fish slime which, as shown by this present work, are proven to be capable of greatly lowering the turbulent friction of flowing water.

It seems quite evident that fish do not depend on a single phenomenon alone to swim more rapidly. Consider the outstanding example of the California bonito,

which is a very fast swimmer, but whose slime showed almost no capability for reducing water friction. Possibly its swift performance is due to the vortex system its undulations generate (Ref. 17), or perhaps to that system plus other natural phenomena which are as yet undiscovered.

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13. ABSTRACT <p>The slimes of a number of species of both freshwater and marine fish were studied for their friction-reducing properties. Most of the species tested displayed a remarkable ability for reducing the friction of turbulent, flowing water. In one species the friction of a diluted solution of the slime was measured as nearly 66% lower than the friction of water.</p> <p>It was found that the properties of fish slime are reasonably similar for individual fish within the same species. Variations in slime properties within the same species are believed to be dependent on the age and size of the individual fish.</p> <p>It is hypothesized that slime properties are dependent on the life habits of the fish and that slime aids a fish's swimming ability.</p>		

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